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The absorption of water by roots

Charles Homer Davis
Iowa State College

THE ABSORPTION OF WATER BY ROOTS

By

Charles Homer Davis

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Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

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I. INTRODUCTION

The necessity of water for plant growth was recognized by primative man. Years of research have added to his information, but still the forces involved in water absorption and the mechanism by which water moves to the plant are not clearly understood. The importance of water to a plant whose tissues may be as high as ninety eight percent water need not be emphasized. The importance of the mechanism by which water is absorbed is magnified in importance when the rate of absorption becomes so small that water is a limiting factor in plant growth. Under all but the most ideal conditions water becomes a limiting factor sometime in the life of a plant. In all except the best years of rainfall, corn, as an example, is checked at some period because of lack of moisture. Plant growth may be stopped even when the soil is high in total moisture content if the evaporation rate is high (27). The regulation of the moisture supply to the plant and the effects on plants of limited moisture will be of especial value to the irrigation farmer, for he is in a position to make immediate practical use of a full knowledge of plant-soil moisture relations. Under dry farming conditions soil moisture determinations are a factor in determining which crops to plant or the manner in which the soil will be prepared for planting. A better understanding of the relation of soil moisture to the growing crop should assist such growers. In addition, it will add to our knowledge of the vital but little understood reactions and conditions at the point of contact between plant and soil.

II. HISTORICAL

Recent Reviews

Two different angles of approach have been made to the soil water relations of plants. The soil physicists have studied the soil and the relation of water to the soil. Many of these physicists have attempted to relate their physical measurements to the growth of plants and so have trenched on physiology. The plant physiologists have studied plants in relation to soil moisture principally from the view point of plant behaviour. A study of plant growth in relation to soil moisture has lead many physiologists to a consideration of the purely physical aspects of soil moisture. The problems of plant growth in relation to soil and the physical states of water in the soil become closely related regardless of the angle of approach.

The purely physical methods of measuring the soil moisture have been recently reviewed by Scofield (36) and Botelho da Costa (3). Surveys of the relation of physical constants to each other have been made by Shaw (37), Keene (22), and Olmstead (29). Olmstead has shown only a slight correlation between the wilting point and other soil constants but relatively high correlations between different purely physical soil constants. Haines (18) and Gardner (15) have considered the soil as a purely physical system and have derived interesting, if not immediately practical, formulas which may be of help in understanding and studying soil moisture problems.

Many attempts have been made to measure the force with which water is held in the soil and the force with which plants absorb moisture. The rates at which water moves when the soil is at or near the wilting point have also been the object of investigation. Accurate readings have been made of soil forces and capillary flow near the saturation point by means of direct suction forces. Shull (39) has reviewed up to 1934 the information on plant soil moisture relations, and, more recently, Lewis (23) also has given a thorough review of this same subject.

The Absorption Zones of Roots

The root hairs have long been considered to be the absorbing organs of the root. The thin walled construction of the root hair, the ready transfer to the cortex from the root hair, and the intimate contact of the root hair with the soil have made the root hair appear to be an admirable absorbing organ, and it has been given credit for the absorption of moisture from the soil. The absorption of water by roots has been tested by means of dye solutions. The technique of the use of dye solutions was described by Popesco (30). Popesco placed roots with root hairs into a dye solution and observed the regions of greatest dye concentration which were assumed to be the regions of greatest water absorption. By means of vital dyes Popesco reached the conclusion that since the absorption of the dye was greatest in the root hair region just above the root cap, the zone of water absorption in the root was the root hair region. Inasmuch as some roots do not develop root hairs he concluded that root hairs were not essential for absorption but were an important aid. He also observed the staining of the vascular bundles and the endodermis, and reached the conclusion that these areas were the water transporting system of the plant and the source of the root pressure which forced the water to the top of the plant. Priestly and Tupper-Carey (31) concluded after studying the growing roots of _Vicia faba_ in dye solutions that the root cap was not an absorbing organ and that the endodermis was the source of pressure for the upward movement of water under root pressure. Shull (39) noted that buckwheat roots took moisture from the soil in a cylinder in an area the size of roots and root hairs, 6 mm, as the roots grew through the soil. He concluded that the root and its hairs absorbed the moisture in a small cylinder as the root hairs penetrated the soil in the progressive growth of the root.

Hehn (21), by use of tubes of various sizes, oiled string and rubber plugs, reached the conclusion that root hairs were not necessary for absorption of water from free water or moist soil. He grew corn plants in which root hair growth on part of the roots was inhibited by excesses of chemicals. Equal numbers of roots with and without hairs were placed in separate containers of water and the relative use of water by the two series was found to be the same. He concluded that root hairs are not necessary for absorption, but still thought that root hairs would be advantageous in mineral and water absorption from the soil.

More recently Sierp and Brewig (40), using some modifications of Hohn's technique, demonstrated that the root cap of Vicia faba would absorb no water and even gave up some water under conditions of plentiful moisture supply. They found that the root hair region absorbed more moisture than other regions of the root but that as the rate of transpiration increased the absorption zone moved toward the plant and stated that dead root hairs became effective in absorption under conditions of high transpiration. The maximum rates of absorption were observed at 40 to 60 mm. from the root tip. The longest roots which they used were in most cases only 7 cm. long.

Similiar results were obtained by Miss. Rosene (35), who used still more improved technique. Miss. Rosene used onion roots which normally do not have root hairs. She grew the onions in moist chambers with the roots suspended in the air. With an ingenious system of universal joints she was able to thread the roots, without touching the roots, through the prepared tips of capillary tubes. The holes through which the roots passed were so nearly the same size as the roots themselves that no appreciable loss of moisture took place from the rings of moisture at the root and tube junction, either by direct evaporation in the moist chamber or by adsorption and capillary creeping along the root. The amount of water used by the various sections of the root was measured by the water absorbed from the capillary tubing. She found that there was an absorption rate gradient from the root tip to the distance of 40 to 60 mm from the tip. All of the root regions except the apex were active in absorption, up to the longest length used, which was 90 mm. Even in this length the greatest absorption was in the region 40-60 mm. from the root cap. She found also the maximum rate of absorption was with roots 40-60 mm. in length. Longer roots had a decreasing rate per unit of absorbing area, thus establishing the maximum rate with respect to age at 60 mm. length. All of the investigations with root hairs, with the exception of Weaver's (47), can be criticised on the point that the root hairs did not develop normally in soil and the roots were not growing in soil. Weaver, growing roots in moist soil, found that under constantly moist conditions root hairs remained active for as long as seven weeks. He believed, however, that the root hairs could remain only in permanently moist conditions, and that they would die as soon as the soil around them became dried by water absorption.

Shull, basing his argument on the data of Popesco, assumed that the roots grew to the moist soil, and that the water of the soil rarely moved fast enough under field conditions to supply the root with water. Lewis, Work and Aldrich (24) studying the capillary flow of moisture in relation to pear tree wilting reached the conclusion that the capillary movement of water is not rapid enough in a heavy soil to permit the whole soil body to be brought uniformly to the wilting point by a pear tree. Lewis _et al_ concluded that there are no data available on the lengths of roots which are active in absorption, and further, that the relation of root distribution to water absorption needs additional study.

The Distribution of Roots in the Soil

The distribution of roots in the soil is an important factor in water absorption. Briggs and Shantz, (9) in defining the wilting coefficient, assumed conditions where the whole soil mass was thoroughly filled with roots. They did not state that the wilting coefficient was the limit of available moisture but that below the wilting coefficient the moisture was not available rapidly enough to maintain turgor in the upper part of the plant. Shantz inferred that roots could grow into dry soil and Breazeale (7) has shown that the roots of some xerophytic species could grow into soil which was below the calculated wilting coefficient. Hendrickson and Veihmeyer (19) found that roots would not penetrate a layer of dry soil more than a few millimeters even though the rest of the plant was growing vigorously. They stated that the withdrawal of moisture from the soil below a depth of a few inches is due almost entirely to roots, and that roots never grow into dry soil. They believed that all the water above the wilting coefficient was equally available and that if all the soil to the depth of normal root penetration was wet at the beginning of the season, subsequent irrigations would not affect the root distribution (20). Beckett and Huberty (2), in irrigation experiments reached the same conclusion. Hendrickson and Veihmeyer state that Weaver et al believe that root distribution is affected by rainfall. It seems likely that Weaver's (47) observations were correct and that the roots simply did not penetrate the dry layers of the soil when there was available moisture near the surface.

The Wilting of Plants

The causes of wilting as such, in relation to the plant and its loss of turgor, have been discussed by Shull (39), and Maximov (28). Although the effect on the plant itself seems to be fairly well established, the relation between the soil moisture and the plant is still obscure. Veihmeyer (42) presents data to show that there is no change in rate of growth of prune and peach trees until the wilting point is reached. The trees grew as well near the wilting point as they did when the soil was near field capacity. Lewis, Work and Aldrich (24) showed that fruit growth in a pear tree growing in a heavy soil with a relatively shallow root system (four feet deep) stopped when there was still ten percent of available moisture in the soil. The leaves showed severe wilting when two to three percent of available moisture was still present. They measured the wilting point with growing plants. They concluded that the lack of uniform distribution of the roots was the important factor in the premature wilting of the tree. The soil samples, as taken by one foot increments, sampled such a large volume of soil in relation to the absorbing areas of the roots, however, that no such non-uniformity showed in the moisture samples.

Alway (1) states that the subsoil moisture, when at or below the field percentage, will remain in place until extracted by the roots which reach that layer. Widstoe and McLaughlin (48) show that roots extract water from all levels but did not determine the actual root distribution. Veihmeyer and Hendrickson (43) showed that prune trees took moisture from the soil throughout the root zone but that the rate of absorption varied with the depth. The trees drew water most rapidly from the surface three feet, a slower rate was noted in the three to six foot area, and only a slight amount of water was taken from the soil between six and nine feet. The trees wilted after the surface three feet reached the wilting coefficient although the lower layers were still above the wilting coefficient. The surface three feet of soil also lost moisture below the wilting coefficient when the trees were allowed to stand in a wilted condition. Veihmeyer stated that when the moisture content of the loam soil reached a rather definite percentage the trees wilted and did not recover until water was added to the soil. Hendrickson and Veihmeyer (20) show that prune trees increased in diameter more when never allowed to wilt than when they either wilted early and had an ample supply of moisture late in the season, or were supplied with ample water early in the season and suffered late in the season. Those trees which suffered for lack of moisture throughout the season increased least in diameter. The size of the fruit was not affected by lack of moisture early in the season. Lack of moisture in the late season was sufficient to reduce the fruit size almost to that of those which had insufficient moisture through the season.

Briggs and Shantz (9) did not define the wilting coefficient as the lowest available soil moisture, but rather, as the point at which the rate of transpiration became greater than the rate of supply of moisture to the roots. They stated that the non-available water for plant use is the water held in air dry soil, which depends on the relative humidity of the air. Alway (1) thought, similiarly, that moisture almost to the hygroscopic coefficient was available for growth. Gradmann (17) stated that plants take water at a reduced rate down to the air dry condition, in keeping with the smaller amounts of water present and the increased work necessary to pull the water from the soil. Breazeale and Crider (8) used three xerophytic plants which removed the moisture from the soil below the calculated wilting coefficient. Caldwell (12), at the Carnegie desert laboratory, found that after wilting under severe drying conditions more moisture was left in the soil by certain species of plants than was left by the same plants when wilted under less severe drying conditions. Brown (10) shows that the Devils claw, a drought resistant plant, in the open when the evaporating power of the air was 7.2 cc. per hour wilted at 15.4 percent soil moisture. Under a lath shelter this species when the evaporation power was 4.1 cc. per hour, wilted at 11.3 percent. In a closed room the evaporation rate was 2.8 cc. per hour and the wilting point was 6.8 percent, in a moist chamber where the evaporation rate was 0.95 cc. per hour the wilting point was 5.2 percent. He placed the plant wilted in the open in the moist chamber and the plant took more moisture from the soil indicating that the higher percentages do not represent the wilting point as usually defined.

Brown (10), Caldwell (12) and Livingstone have all been critisized by Botelho da Costa (3) because they did not follow the method of testing in a moist chamber for 24 hours to determine if the plants would recover. The time of 24 hours is an arbitrary one chosen by Briggs and Shantz for their experimental work. Should two pots or jars be placed in a moist chamber and one recover in twenty of the twenty four hours and the other not only a little drier just fail to recover and be set into the greenhouse for another day, then the evaporation in a day will need to equal the difference in recovery for four hours or the moisture determinations will be sensibly different. The amounts of moisture extracted in a day by the plants used in the wilting experiments have not been published nor the differences in moisture percentages between duplicate pots at the time wilting was observed. Veihmeyer's data on prune trees in orchards, and the relatively small number of old plants used by Briggs and Shantz, are the only mature plants used in wilting point determinations. If the wilting point is a specific soil constant plant age should not affect the determination except through root distribution; on the other hand wilting percentage has not been determined with many mature plants.

Lewis (23) as stated earlier, has noted the need for research on the relation of root distribution and extraction of water from the soil by plants The published data of Lewis, Work and Aldrich (24) seem to be the only information on this important phase of plant research. They used trenches dug in the root zone of a mature pear tree and determined the root concentration by weighing all of the roots of 2 mm. or less in diameter which occurred in a given soil volume. They found a high correlation between the presence of roots and the rate of moisture absorption shown in the previous season's records of soil moisture extraction in both the lateral and vertical root areas. They found that water was used most from the surface foot, at about the same rate from the second foot and the third foot, and at a slightly lower rate from the fourth foot. Root concentrations were in the same order. When studying lateral distribution they found fewer small roots in the two feet nearer the tree than in the area two to four feet from the tree where the water use was greater. As they sampled farther from the tree, to a distance of fourteen feet, both the amount of water absorbed and the weights of small roots decreased, in about the same order. Veihmeyer and Hendrickson (45) observed similiar absorption with peach and prune trees. More water was taken from the upper three feet where they believed root concentration was higher than from three to six feet deep or six to nine feet deep. They did not, however, have measurements on the same volumes of soil.

Water Movement Near the Wilting Point

The methods used in the study of physical properties of soil water have been accurate in the extreme ranges of wetness and dryness. In the range of plant use which is intermediate, the methods have been inaccurate. As early as 1907 Buckingham (11) had determined the percentage of moisture left in the soil after water had reached equilibrium by capillarity. Buckingham's curves are similiar to those later obtained by Gardner (15), Shull (38), Edlefson (14) and Botelho da Costa (5). A significant recent contribution has been made by Lewis (23) who used six inch columns of soil with the field structure essentially preserved. He took samples with the King tube into which had been inserted a celluloid sleeve which received and held the soil sample. He lacked length of Soil Column in this experiment but undoubtedly gained much by preserving field structure. He regulated the amount of moisture which was put into the soil either at the upper or the lower end and passed a warm drying current of air over the other end. He regulated the amount of water added so that he could add more to increase steepness of the moisture gradient from supply to evaporating surface or add less to decrease the gradient, and thus regulated the final moisture content of the surface when the soil had established a uniform rate of flow. From these flow data he calculated the transfer on a gradient of moisture content per unit of moisture per unit of time over a definite area. He has shown that there is a slight loss of moisture from the surface when a soil is near the wilting percentage and that the rate of loss is governed by the moistness of the surface soil and the soil supplying the evaporating surface with water. This point had already been shown by Widstoe and McLaughlin (48). The data of Lewis (23) suggest that there was an appreciable transfer of moisture by the soil near the wilting percentage. Over the large area of the surface of the roots of a plant the total amount of water moved to the plant even at these moistures might be considerable. Soil columns, the surface of which were near the wilting point, transferred moisture at the rate of two inches per month. That the moisture was not transferred in the vapor phase was demonstrated in an experiment in which the column of soil was broken one to seven centimeters from the surface by a gap one millimeter in width. Through the gap a steady flow of eleven milligrams per day of moisture was established. The difference between the moisture below and above the gap was twelve to seventeen percent. Conrad and Veihmeyer (13), and Shull (38) and others have shown, however, that the rate of flow of capillary moisture near the wilting point is not rapid enough to supply the plant with the moisture it needs. Data by Breazeale (7) who grew plants in soil which was below the wilting coefficient, with the roots dipping in water below the soil, indicated that wheat plants could put moisture into the soil. It has been suggested that this, and other work indicating apparent discrepancies should be checked.

The forces involved in the vapor tension of the water at wilting have been variously estimated at between four and twenty-five atmospheres. There is a certain lack of uniformity in expressing results so that it is difficult to compare the values used. However, most of the recent results point to a value close to sixteen to twenty atmospheres. Botelho da Costa (5) revised Bouyoucous' (6) method of determining the freezing point of the soil, and from these data calculated the vapor tension, which he expressed as the log of the water column which would be supported by that force. He showed that the wilting coefficient as determined by Veihmeyer was in the range of pF 4.0-4.4 with an average value of 4.2, or aproximately fifteen atmospheres. Olmstead (29) has shown a progressively decreasing moisture content after centrifuging under increasing gravity. He did not determine the wilting point on the soils he used.Centrifugation with provision for contact with a free water surface may show promise as a means of determining directly the free-energy of the soil at any specific moisture content. Gardner (16) used both moist and dry absorbent paper which came to equilibrium in the soil and showed a smooth curve for tension in the soil. The standardization of his paper was made in the wet range by means of a centrifuge and in the dry range by means of vapor equilibrium over sulfuric acid solutions. His value for tension in the range of wilting must be determined by interpolation. Shull (38) and later Wolfe (49) used seeds of Xanthium, much as Gardner (16) used the filter paper. The values which they determined seemed to be about sixteen atmospheres.

Vapor pressure measurements have been made by Puri, Crowther and Keene (32) in an attempt to determine the relation of vapor tension and soil moisture percentage. Similiar determinations by Edlefson (14) showed that the tension at the wilting point as measured by the vapor pressure is near twenty atmospheres. Vapor pressure determinations are time consuming and are more valuable in the range of hygroscopic moisture than for moisture in the range of growing plants.

Livingstone and Koketsu (26) used a porous clay cone to determine the water supplying power of the soil; their unit is standardized for absorption from a moist chamber. They obtained thus an estimation of the rate at which water can be supplied to a plant. When the same point was used under the same conditions, readings were comparable but not in known units. The soil point method does demonstrate the dynamic nature of the soil moisture supply to the plant.

Much is still to be learned about the relation of the dynamic forces at wilting. The meager knowledge of the tension of soil water and the rate of change of tension, or capillary potential, with changes in moisture and temperature makes difficult the determination of the nature of the soil moisture at wilting. The nature of the changes which occur in that part of the plant above the soil at the time of wilting are fairly well understood. The knowledge of plant behaviour below ground as related to drying conditions in the field is little understood. It was with a desire to add information to the nature of the water absorption by plants in the field that the work hereinafter reported was undertaken.

III. EXPERIMENTAL

A. Method of Procedure

Root distribution in relation to water absorption from the soil was studied through a glass-front box. During the course of these experiments two such boxes were constructed. The first box was constructed around a plate glass fifty inches long and eleven inches wide. The inside dimensions of the box were fifty inches long, eleven inches deep, and four inches wide. The first box was filled with soil to within one-fourth inch of the top of the glass. The box was so constructed that it was possible to remove the glass in order to obtain samples of soil from near the roots. A black cardboard was held against the front of the glass to exclude light. The open side of the cardboard was painted white. The second box was built in the greenhouse at Tucson and was fifty-three inches long and ten and a half inches deep. This box was also provided with a glass front which was sealed to the wood of the box. All of the wooden parts of the second box were painted with hot parrafin and set in the sun, so that the wood surface was thoroughly soaked with paraffin. The cracks and joints were filled with paraffin or a mixture of paraffin and sawdust so that the box was water tight except for a drain at one end. The box was filled with soil to within one inch from the top.

The soil was packed in the boxes after thorough mixing, in layers parallel to the bottom of the box so that any stratification which might occur would be the same through the length of the box and would be apparent against the glass fronts. The uniformity of the soil surface against the glass, and the uniformity of a test series of soil samples, indicated a uniform moisture throughout the box. Twelve tensiometers, as described by Richards and Gardner (33), were set at four-inch intervals in the first experiment, with the porous clay cups of the tensiometers six inches from the surface and two inches from both the back and the front of the box. The soil was covered with a mixture of sixty percent paraffin and forty percent vaseline. The soil at Tucson was covered with paraffin alone and sealed to the paraffin impregnated wood on all sides.

The soil used at Ames was Clarion Silt Loam. The wilting point of this soil, determined with corn plants, was 8.5 percent. The soil used at Tucson was Gila Silt Loam and had a determined wilting point of 6.7 percent. These soils were similiar in all respects, except for the humus content. The Clarion soil was much higher in humus than the Gila soil. The soil at Tucson came from a field which had been so treated that the organic material was fairly high for a desert soil but was still much lower than the Clarion soil. The water holding capacity of the two soils, as measured by the percent of water held by the soil when wet from the surface of a two gallon pot and in equilibrium with a dry layer of soil at the bottom, was very nearly the same. The soils after screening and placing in the box did not have field structure. After wetting and drying some structure may have been formed but the structural relation of the soils used in this experiment to the same soils in the field is remote.

The tensiometers in the first experiment were read daily. Moisture determinations by direct sampling were made irregularly at the first of the experiment and later at weekly intervals. The soil moisture samples were taken at weekly intervals at Tucson, except where watering interfered with the schedule. Moisture samples were taken with a steel tube of one-half inch inside diameter. The leading end of the tube was beveled from the outside to make a cutting edge and the tube was smoothed on the inside. The tube cut a cylindrical cone of soil one-half inch in diameter and of various lengths depending on the depth to which the tube was pressed when sampling. The cores were lifted from the soil and emptied, into weighing flasks or soil cans, by tapping with an iron rod against the side of the tube. The soil sample was weighed and dried for twenty-four hours at 105°C, reweighed and the percentage of moisture calculated on the oven dry weight.

Corn was planted at one end of the box and the roots observed as they grew through the soil. The corn used for seed at Ames was a field corn furnished by Dr. A. A. Bryan. The corn seed used at Tucson was Golden Republic, a relatively hard seeded yellow dent selected for its uniformity under Tucson conditions. A record was made of the root tips which showed on the glass in the box at Ames. The record at Tucson included the numbers of live roots exposed against the glass for each inch of distance from the corn plant. The area included in each count was from the bottom to the top of the box and thus was an area of soil one inch wide and nine and a half inches high.

Corn plants were grown in sealed two gallon pots for wilting point determinations until the central leaf was definitely wilted. The pot was then opened up, the seal and top soil discarded, and moisture samples taken from the remaining soil. Glass jars or glazed pots were used for these determinations. An attempt was made to get growth curves in relation to tensiometer readings at Tucson but the tensiometers would not stand up under the conditions which prevailed.

A series of four pots was planted with twenty corn seeds each. The plants were thinned to ten in each pot when the plants were approximately one-hundred millimeters high. The weight of the empty pots, the wax, the soil and soil moisture were determined before planting and checked at the end of the experiment. With these data the weight of the water could be calculated and also the percentage of moisture from the gross weight of the pot. The final moisture percentages were used because of an error in filling pot three, so that the weight of soil calculated from the first weight was too low, and because more moisture samples were taken for each pot at the end than had been taken at the time of filling. The difference in calculating the moisture on final or original moisture content of the soil has little effect on the moisture percentages during the course of the experiment. The greatest height to which the leaves could be pulled was measured daily for each of the ten plants in each of the pots. At the same time that the heights were measured the weight of the pot was taken and the temperature recorded. The measurements unfortunately were not taken at the same time each day. The intervals, therefore, were not uniform. There were some breaks in the records when the measurements were not made because the experimenter was out of town.

An attempt was made to check some of the work of Breazeale (7), using corn plants. In most cases the corn plants would not survive the treatments.

The method of Shull (38) and Wolfe (49) was modified, using corn as an osmometer in the soil. The method was standardized so that fairly consistent results were obtained and the error of the experiment was quite low. The corn was dried at 80°C for twenty-four hours. Corn will lose some moisture after this period but the daily rate of loss is consistent and continuous. The corn seed was planted in cane sugar solutions for the measurement of the forces against which it could absorb moisture. The time necessary to reach equilibrium was determined and the corn seed dried and weighed.

B. Results

I. Water absorption

Experiment at Ames. A glass front box in the green house at Ames in which corn was planted, February 2, 1937 was wet from the top so that moisture drained from the bottom. The soil was then sampled at intervals of one to two days, so that six soil samples were taken in the course of eight days. The samples were taken by three inch increments in depth so that at each location there were three determinations for each day. The box was sampled in four locations. After sampling the holes were refilled with soil. The percentages of moisture found in the samples are shown in Table I. These data were subjected to an analysis of variance as shown in Table II. The locations did not differ significantly in moisture content. Days and depths did differ significantly. The totals for depths are; 476.57 for the surface to three inch depth, 475.71 for the three to six inch depth, and 459.76 for the depth from six inches to the bottom. The error term for depth is the sum of squares for the interactions of day times depth and location times depth. The low interaction for location times depth shows that the soil was uniform in moisture percentages at the same depths for the different locations and lowers the error term for depths. It is not likely that there was a real difference due to depth unless there was less packing or lack of penetration of moisture to this depth. The soil was not covered with any protective seal during these preliminary drying tests and the differences, though significant, showed losses from a moist unprotected soil were only of the order of two to four percent in a week.

TABLE I

Moisture Percentages of Soil Samples Taken for Test of Uniformity from Box in Greenhouse at Ames During the Period February 3rd to 10th, 1937, Before Corn Roots Had Grown into the Soil.

Date	Inches Depth	Location Between Tensiometers 4-5	6-7	8-9	10-11
2-3-37	1-3	26.83	20.88	17.33	21.33
	3-6	22.83	23.88	21.52	22.03
	6-10	23.33	19.44	19.30	20.90
2-5-37	1-3	24.24	20.75	20.00	20.99
	3-6	19.48	20.51	19.38	20.16
	6-10	20.28	19.82	21.43	19.74
2-6-37	1-3	19.01	18.64	19.01	19.20
	3-6	18.80	19.47	18.18	18.92
	6-10	18.40	18.26	18.18	19.40
2-8-37	1-3	17.92	18.81	20.00	19.37
	3-6	19.74	18.92	19.70	18.67
	6-10	17.39	19.85	18.79	18.45
2-9-37	1-3	18.92	19.90	21.43	17.31
	3-6	18.03	18.45	19.42	19.05
	6-10	17.36	19.26	20.21	18.08
2-10-37	1-3	18.09	18.51	20.51	18.49
	3-6	18.58	20.80	20.59	18.55
	6-10	18.12	17.83	17.39	18.60

TABLE II

Analysis of Variance for Moisture Samples Taken from Open Soil in a Green House Box. Data are Shown in Table I.

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F
Total	131.05	71		
Days (Da)	86.754	5	17.3508	16.50**
Location (L)	2.241	3	0.7470	1.076
Depth (De)	7.861	2	3.9305	5.350*
Da X L	14.571	15	0.971	
Da X De	11.711	10	1.171	
L X De	0.002	6	0.0003	
Da X De X L	7.910	30	0.264	
Error Terms				
Days	26.282	25	1.0513	
Location	14.573	21	0.6940	
Depth	11.713	16	0.7358	

** Denotes an F value above the one percent level of significance (41)

* Denotes an F value above the five percent level of significance

The first roots of the corn showed against the glass front on February 11, 1937 and their location was marked with a wax pencil. The tensiometers had been read daily, the readings are shown for two day intervals in Figure I. The tensiometer readings in Figure I are graphed from the top down so that the lines represent the level of moisture in the soil, for a given day. The lateral root extension for the various days given on the chart is shown by means of lines at the top of the page. The tensiometers are numbered from the planted to the unplanted end of the box and are shown in their relative position to the root extension lines. The days omitted showed the same type of curve and would have added nothing to the information while merely confusing the lines on the chart. The gradual, uniform lowering of tensiometers beyond the root zone was due to air drying.

It is noted that on the dates February 11 and February 13 very slight increases in tension or lowering of moisture were recorded near the plants. The roots had extended beyond tensiometer #2 on the fifteenth, and there was some removal of water at tensiometer #3 by February 17, but tensiometer 12 which was three and one-half feet from the plant showed an equal reduction, thus suggesting a chance effect rather than capillary movement of water to the nearby root zone. The roots had extended to tensiometer #3 on the

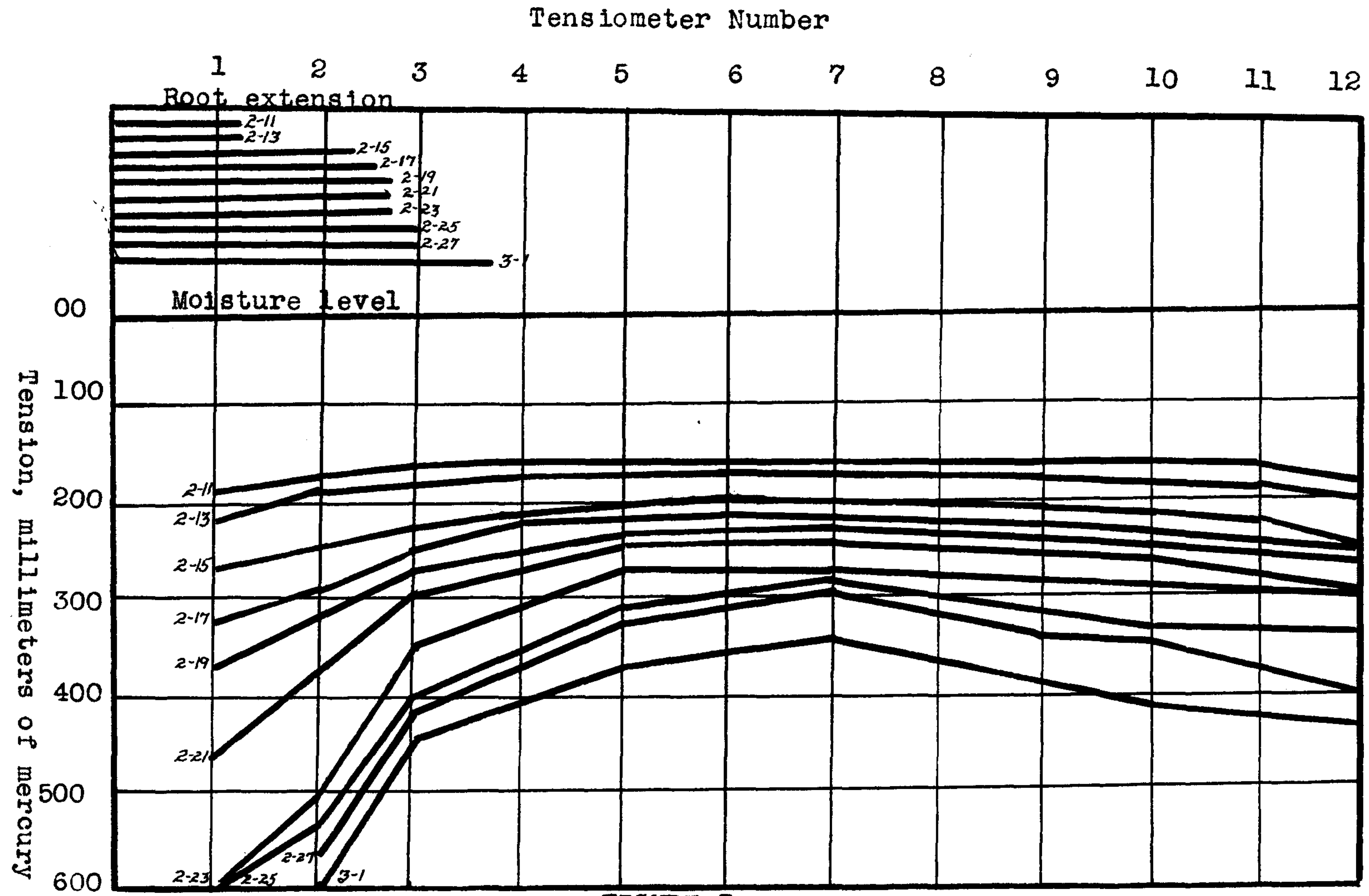

FIGURE I
Moisture absorption as indicated by increased soil moisture tension in a glass-front box, and the lateral root extension on the same scale.
Ames. February 11, to March 1, 1937

twenty-fifth to twenty-seventh, and a slight lowering of moisture was noted in tensiometer #3. Four days later, when the roots had grown three inches past tensiometer #3 only a relatively small quantity of water had been removed from the area near tensiometer #3.

The tensiometer readings changed very little from March 1 to March 15, when the plants were wilted. The lateral root extension had reached only one inch farther on March 15 than the advance on March 1.

The entire box of soil was moistened on February 15. By February 18 a slight rise in tension was noted near the plants (Figure 2). The moisture absorption by two day intervals are shown on Figure 2, in which tension is graphed reciprocally so that the lines represent soil moisture. The lines at the top of the chart show lateral extension of roots for the days marked. The significant facts in Figure 2 are the relation between root extension and moisture lowering. During the period shown in Figure 2 no root tips with hairs appeared closer to the plants than sixteen inches, or between tensiometers #4 and #5. Water absorption took place in the region between tensiometer #3 and the plant until March 26. The roots had extended almost to tensiometer #8 on March 26. The roots had extended to within one inch of tensiometer #9 on March 31 but appreciable moisture absorption did not occue near tensiometer #9 until April 6 when the roots had reached

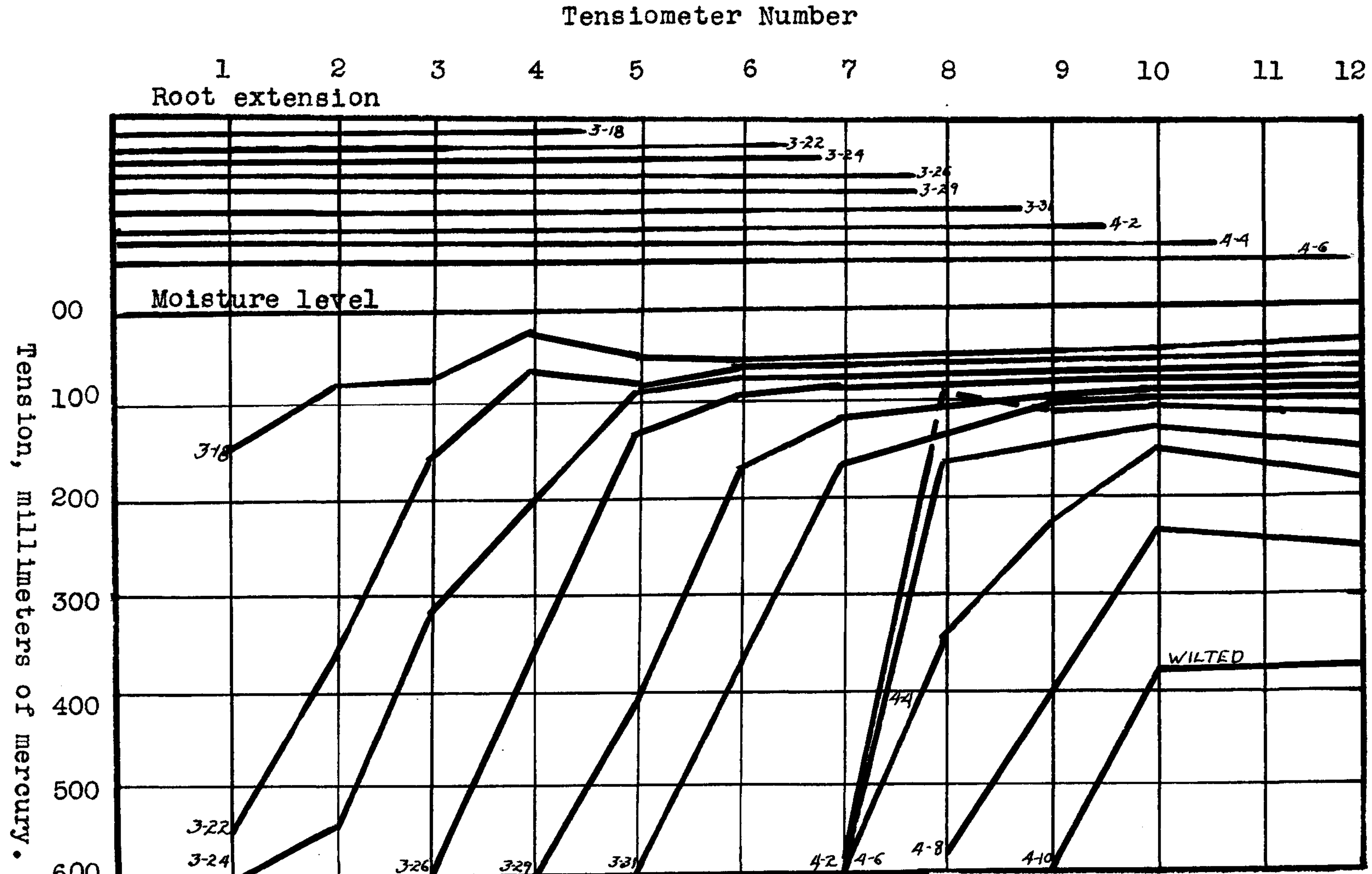

FIGURE II

Moisture absorption as indicated by increased soil moisture tension in a glass-front box, and the lateral root extension on the same scale.
Ames. March 18, to April 10, 1937.

the end of the box. Moisture absorption took place near tensiometers #10 and #12 on April 8 and April 10. There was not enough moisture at any place in the box to be measured with the tensiometers after April 11. This does not mean that the soil was dry but that at no place did the moisture exceed fourteen to sixteen percent. The actual soil moistures percentages as distributed by time and location, are shown in Table III with the estimated numbers of roots. The estimate of root number are the total of all root tips appearing in the area during the course of the experiment until April 26. After April 26 the new root tips were few and scattered in time and location. On April 10 the plants were wilted and remained wilted for six days, until the box was re-wet. The samples of April 16 were taken before the box was wet. The samples of April 16 show that the roots, at least to two feet, were in soil as dry as the wilting point for these plants.

Between tensiometers #9 and #10, forty inches from the plant, there were seven roots six of which had root hairs. The roots had been present in this soil for fourteen days and the soil still held 11.2 percent of moisture. The sample taken in the lower layer with the roots without root hairs had less moisture than the area in which the root hairs remained alive.

The tensiometers were again put in working order after the soil was wet and on April 19 the first accurate

TABLE III

Moisture Percentages by Date and Tensiometer Locations and Numbers of Roots Appearing Each Four Inches in a Box at Ames.

	Tensiometer Location													
Date	1	2	3	4	5	6	7	8	9	10	11	12	Depth of Samples	Notes
3-11				13.5					15.2				1-3	
				13.0					16.1				3-6	Wilted
				13.8					14.1				6-10	
Roots	16	21	14	9										
3-12		18.5							19.2				1-3	
		14.7							14.6				3-6	Re-Wet
		12.0							15.3				6-10	
Roots	16	21	16	9										
3-17			21.3							24.6			1-3	
			22.9							22.8			3-6	
			20.0							25.8			6-10	
Roots	16	21	16	14										
3-29		12.5				18.5				24.8			1-3	
		10.5				19.0				21.8			3-6	Re-Wet
		9.7				19.1				21.7			6-10	4-9
Roots	16	22	16	19	5	9	5	2	1					
4-16			7.9			8.1			13.3				1-3	
			8.1			7.4			11.0				3-6	Re-Wet
			7.1			7.5			9.2				6-10	
Roots	16	22	16	23	14	23	16	9	7	2	2			

TABLE III (Cont.)

Date	1	2	3	4	5	6	7	8	9	10	11	12	Depth of Samples	Notes
						Tensiometer Location								
4-18				25.2			29.6		27.0				1-3	
				20.7			23.1		24.1				3-6	
				9.0			21.5		21.6				6-10	
Roots	16	22	16	23	14	23	16	12	7	5	2			
4-26	9.6			12.5			14.9		19.2				1-3	
	9.9			11.4			14.3		17.0				3-6	Wilted
	10.4			10.1			13.5		15.9				6-10	5-5
Roots	16	22	16	23	14	23	16	14	13	17	14			
5-7			7.1				7.5			11.3			1-3	
			7.1				8.1			9.2			3-6	
			7.0				7.3			8.5			6-10	
5-10			21.6				21.3			22.0			1-3	
			21.9				21.7			22.9			3-6	Re-Wet
			23.3				22.8			24.0			6-10	
5-15	8.9			12.8				18.0					1-3	
	9.0			13.4				18.3					3-6	
	8.5			11.4				19.2					6-10	
5-22		7.5							14.3		18.3		1-3	
		8.1							13.3		18.3		3-6	Wilted
		7.8							12.3		18.2		6-10	
5-29			7.3				7.9				15.9		1-3	
			7.5				9.3				15.5		3-6	
			7.0				8.2				15.3		6-10	
6-8	9.5		16.4						19.4				1-3	
	9.5		14.0						19.8				3-6	
	9.2		13.9						20.3				6-10	

readings were obtained. These figures are shown in Figure 3 which is similiar to Figures 1 and 2 except that the roots had extended to the end of the box and after April 26 were uniformly distributed in the soil. The tensiometer readings in Figure 3 show that the moisture percentage was lowered in the area near the corn plant before moisture was taken from greater distances although the observed root concentrations were similiar in the two areas. The trouble encountered with the tensiometers is shown graphically on the line for April 24. Either because of fault in the tensiometers or because the soil was dry numbers two, three, four, and five were out of order. Tensiometer #1 still showed a reading and no visible trouble. Tensiometer #1 finally reached a reading of 523 mm on April 26 when a soil moisture sample taken near the clay cone showed 9.6 percent. Tensiometers usually failed to register well above this point. Tensiometer #1 may have been so thick walled that it did not lose water during this time in response to the lowered soil moisture.

The soil moisture samples, Table III taken on April 26, show a moisture gradient from the plant to the opposite and of the box. No root hairs appeared nearer the plant than tensiometer #9. Between tensiometers #9 and #10 where root hairs were most abundant the moisture in all levels sampled was adequate for plant growth. The plant wilted severely on May 5 and did not recover until wet on May 8. Samples

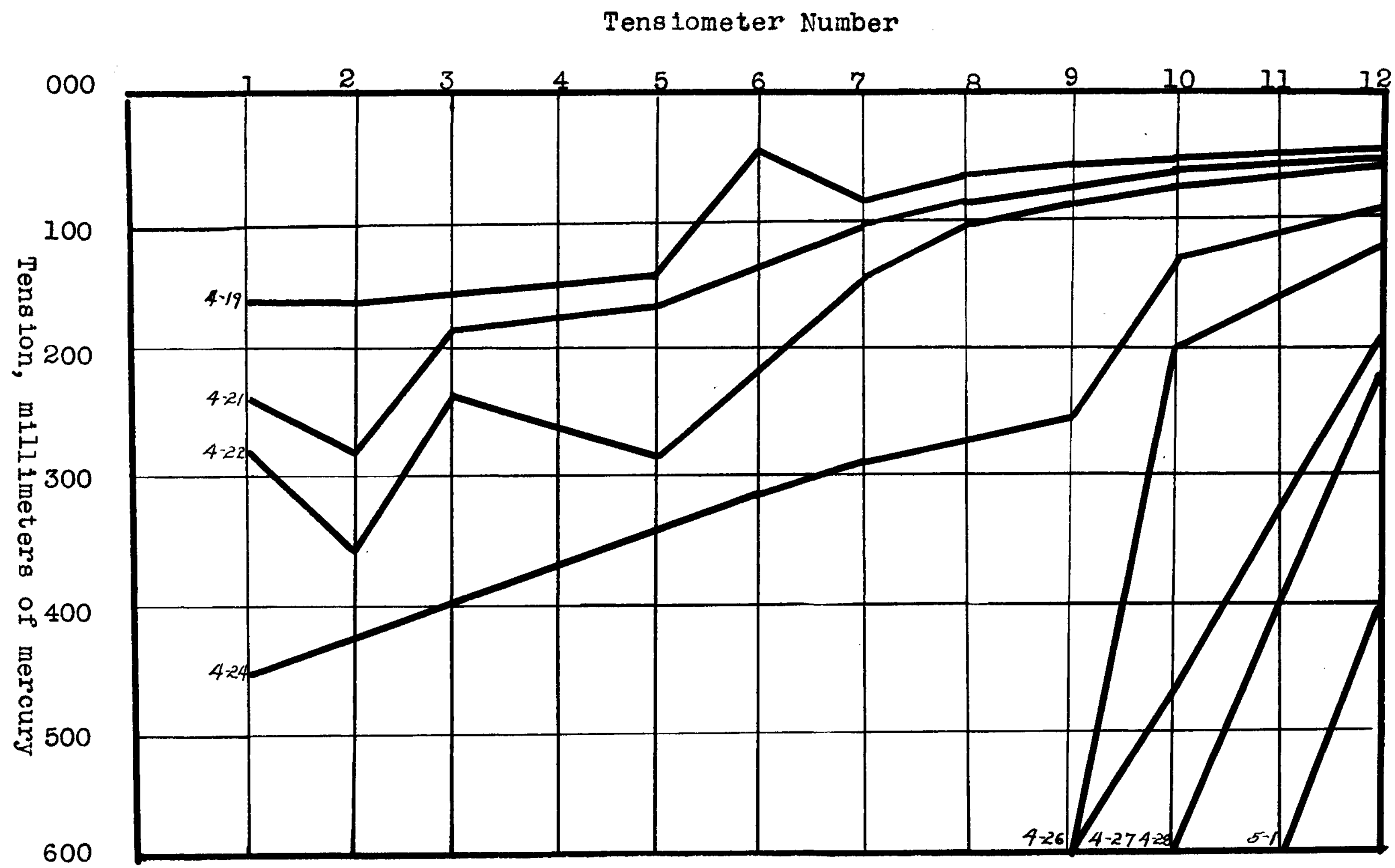

FIGURE III
Moisture absorption as indicated by increased tension in a box completely sampled by corn roots. Ames. April, 19 to May, 1, 1937.

taken on May 7 showed that there was some available moisture four feet from the plant but the plant was apparently not able to use it for growth or to regain turgor during the night.

Tensiometers were again put in working order and on May 10 the first readings were recorded. The readings are charted by two day intervals in Figure 4. When the box was wet on May 8 all of the root hairs had died and after this date only a few scattered root hairs appeared against the glass front. The percentages shown on Figure 4, for the date May 22, are moisture percentages determined for these locations and also appear in Table III. During the period shown in Figure 4 the roots were uniformly distributed in the box. The moisture first disappeared near the plant and lastly in the areas farther from the plant. The plant finally wilted when the soil four feet away was still practically saturated.

The moisture samples were taken at approximately weekly intervals after May 10 when the soil was wet uniformly. These data are shown in Table III. On May 15 the soil was close to the wilting point near the plants while sixteen inches away there were appreciable quantities of available moisture, and thirty-two inches from the plant there was an excess of water. The plant wilted on May 22 when available moisture was present 16 inches from the plant, and the soil was within two to three percent of field capacity forty-six inches from the plant. The soil still held available water forty-eight inches

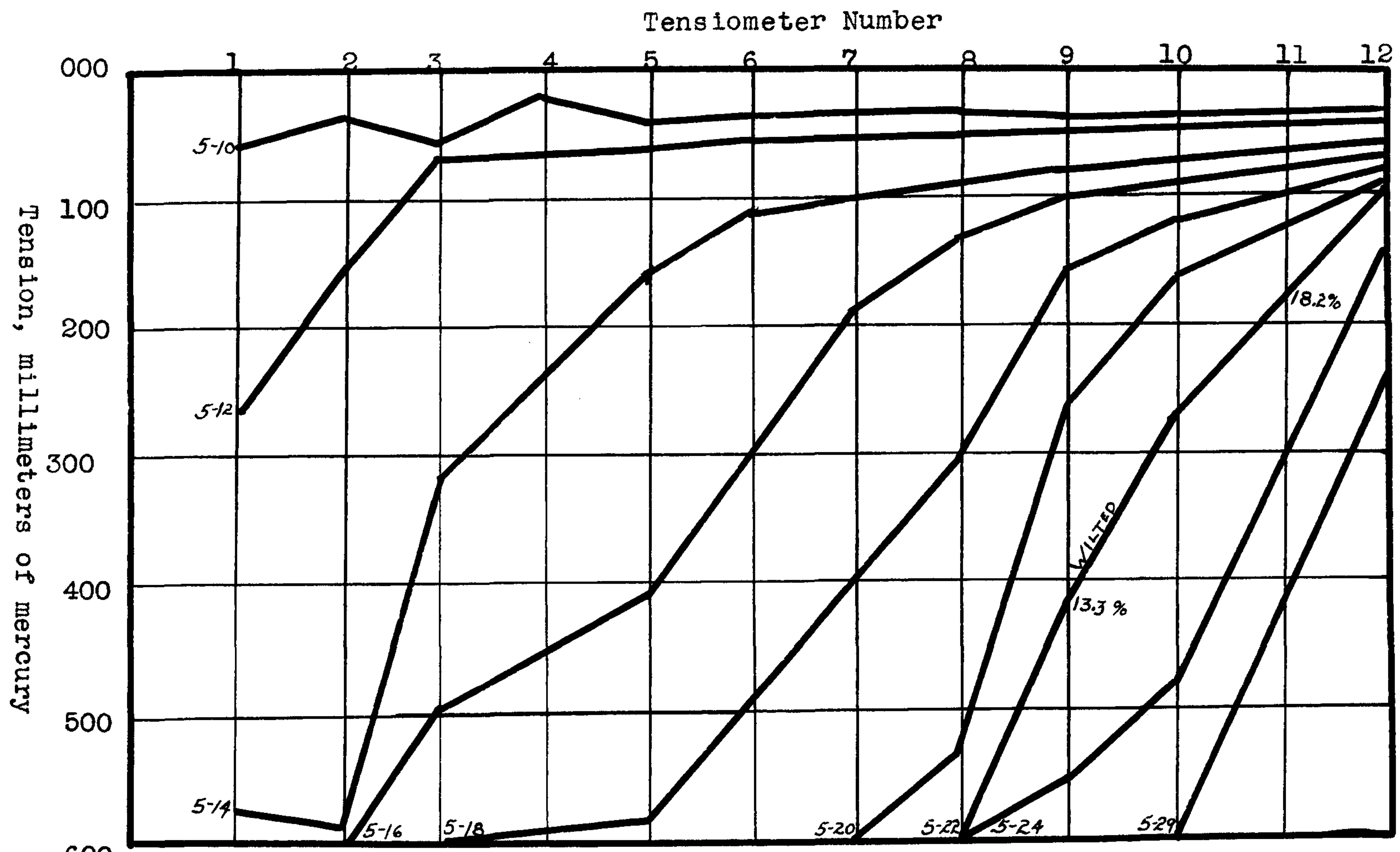

FIGURE IV

Moisture absorption as indicated by increased tension is a box uniformly filled with corn roots. Ames. May 5, to May 29, 1937 from the plant on May 29 and three root tips with live root hairs were present in the upper right corner of the box. The plants were so severely wilted that they were almost dead. The box was wet and re-wet on May 31 and the next moisture samples taken on June 8. The last samples showed that the moisture still disappeared from near the plant while the soil as close as one foot held at least two-thirds of the normal available moisture. Three feet from the plant only a negligible amount of moisture was taken by the roots.

Experiment at Tucson. Corn was planted October 28 in a glass-front box at Tucson and thinned to one plant on November 3. Moisture samples were taken from the top to six inches deep and from six inches to the bottom of the box. The moisture percentages of the samples taken are shown in Table IV. The roots were counted for each date and appear in Table IV, summed for each four inches along the front. The cracks which occurred in the soil after wetting and drying were filled with soil on November 4 and wet again. The last cracks were filled November 9 and the soil moisture samples taken November 10. The soil was not packed in any way before being wet and it was hoped that the wetting and drying would give soil near the field condition. The soil surface which had been smoothed in the two fillings was covered with paraffin. A total of 40.050 Kilos of soil calculated to the oven dry weight, was placed in the box. The volume occupied by this

TABLE IV

Moisture Percentages and Root Distribution by Four Inch Intervals in the Box in the Greenhouse, Tucson.

	Distance From the Plant in Inches												
Date	4	8	12	16	20	24	28	32	36	40	44	48	53
11-4		4.74			7.72				9.61				
		7.56			7.91				12.13				
Roots	-	3											
11-10			24.9	23.3	21.8					22.2			
			29.4	17.3	22.5					24.8			
Roots	-	3	-	-	1								
11-19		8.3		9.1			14.4			14.6			
		7.6		9.1			15.3			15.2			
Roots	5	3	10	5	3	2							
11-21			6.1			10.4		11.4			11.9		
			7.1			9.2		13.0			14.6		
Roots	8	14	16	21	17	12	9						
11-29*		7.2			13.4			15.6			18.7		
		7.7			9.3			16.6			22.0		
Roots	12	23	33	52	50	52	24	9					
12-7*	3.1					6.4		9.5	11.8				
	5.1					5.6		9.7	14.6				
Roots	19	29	31	53	52	51	20	17	4				
12-8*			3.6				6.2						
			5.3				6.8						

* Denotes the days on which the plant wilted.

TABLE IV (Cont.)

Date	Distance From the Plant in Inches: 4	8	12	16	20	24	28	32	36	40	44	48	53
12-14													
Roots	27	31	39	61	62	67	30	40	5				
12-18			10.0		12.6					16.4		18.9	
			9.8		11.1					18.8		19.2	
Roots	28	33	37	65	83	69	32	56	43	28	15		
12-21		6.7			9.5			13.2			15.7		17.3
		8.3			7.7			10.9			17.9		19.3
Roots	40	33	51	71	86	77	33	70	66	54	39	3	
12-24*				5.8		7.9					13.2	13.2	
				6.2		7.1					12.2	15.0	
Roots	36	34	48	58	73	58	36	69	53	59	47	10	
12-27	23.3		30.1					29.4				34.3	
	24.0		25.5					29.9				34.4	
Roots	41	36	49	57	75	60	39	64	64	68	52	28	30
1-1		17.1		19.2				19.1		25.5			24.5
		16.4		19.1				21.4		24.9			25.7
Roots	37	33	45	61	80	64	39	50	60	71	70	52	28
1-2	11.0		16.2		16.9	21.6		21.5		20.0	22.3	24.1	25.3
	14.8		16.9			20.2		22.9			24.8	25.0	

* Denotes the Days on which the plant wilted.

soil was 29,869.02 cubic centimeters or 1.3408 grams per cc.

Root counts were made on an area one inch wide and nine inches high along the front of the box, extending from the plant which was at one end of the box. The figures in Table IV are each sums for four of these areas. The lower figures for each date represent the number of roots which were alive and could be seen through the glass in the area from the plant to four inches from the plant, from that point to eight inches, and so on, until the roots from forty-eight to fifty-three inches appeared on December 27. The soil moisture samples were taken in the same areas. The mature corn plant actually grew against the left end of the box and its relative position would be at the left of Table IV. The story of moisture loss is shown to be the same as for the box at Ames. When the moisture dropped to fourteen or fifteen percent at forty inches on November 19, and again to 11.86 and 14.56 percent at forty-four inches on November 21, the paraffin seal was checked closely and found to have become brittle, either through too much sun or through absorption by the soil. The paraffin was then covered with new paraffin to a depth of one-fourth to three-eighths of an inch. The lower node of the corn plant was covered with a dead leaf sheath and the melted paraffin was poured around the plant. Circles of paraffin were cut out with the soil sampling tube before the samples were taken and these circles were sealed back over the same holes after the holes were refilled.

The moisture percentages in Table IV show that on November 19 the plant had reduced the moisture to near the wilting point within eight inches of the plant. Sixteen inches from the plant the soil had 9.09 and 9.15 percent moisture. Twenty-eight inches from the plant the soil moisture was 14.39 and 15.29 percent. At forty inches, where no roots occurred, the soil was only slightly different. The same picture is shown on November 21, when the soil was even drier then the wilting point twelve inches from the plant and available moisture was present in the region which the roots penetrated farther from the plant. The plant wilted in the afternoon of November 29 and moisture samples were again taken. The roots were fairly numerous at thirty-two inches and yet the wilting plant was unable to obtain the moisture fast enough to maintain turgor. The plant wilted at ten A. M. on December 7 and moisture samples were taken again. The surprisingly low values were checked again on December 8, the samples being taken far enough from those of the previous day that the soil used in filling the first sample holes would not affect the new determination. The moisture percentages of 3.60 and 5.34 at twelve inches, and 6.16 and 6.83 at twenty-eight inches are lower than similiar plants were able to reduce the moisture in sealed pots. Some of the roots were in moist soil on December 7 at a distance of thirty-six inches from the plant. The soil was wet after the December 8 sampling when the plant did not recover turgor over night.

Samples were taken on December 14 and root counts made but unfortunately the soil moisture samples were lost. The roots had extended to forty-four inches by December 18. The moisture was lowered near the plant but at forty inches the roots present had not lowered the moisture appreciably. The plant wilted at one-thirty P. M. on December 18 when the temperature of the greenhouse reached 89°F. The greenhouse was opened and at four P. M., when the temperature had dropped to 75°F, the plant had regained turgor. On December 21 the plant was wilted in the evening but had recovered by morning. The roots then had almost reached the end of the box and some root growth was occurring throughout the box. There was a tendency for the roots to grow first along the bottom of the box and as they extended, for more roots to appear toward the top of the soil. Such moisture figures as those for November 21 at twenty-four inches and for November 29 at twenty inches show the difference in water absorption due to the greater numbers of roots in the lower layers.

The plant was severely wilted on December 24 and had been wilted continuously for two days. Soil samples showed that the moisture was below the wilting point one foot from the plant but above the wilting point at a distance of forty four inches, where as many roots were located as near the plant.

The decrease in numbers of roots near the plant in the period December 24 to December 27 was due to the death and drying of some of the small roots. The box was thoroughly wet on December 27. At this time, the drain was stopped accidentally, with the result that the soil mass was above the saturation point. On the first of January the plants had taken moisture out of the soil near the plant so that the soil moisture was below field capacity at a distance of sixteen inches from the plant. The soil moistures thirty-two inches from the plant was above the field capacity. The glass front was taken from the box January 2 and the soil samples taken at different points in the box. The moisture distribution at this time indicates that when roots were equal in number near the plant and forty-eight inches from the plant more water was absorbed near the plant than forty-eight inches from the plant even though the water forty-eight inches from the plant was above the field capacity.

Root counts were made at the surface of the glass on January 2 before the glass was removed. The soil was divided into three inch increments from the plant. Three inch sections seemed to be as small as the soil could be divided without excessive crumbling and breaking of the smooth surface. The soil was cut away from the end of the box, the first of the sections to be counted exposed by washing with water, and the roots of any size counted. The counts of roots appearing in a plane perpendicular to the length of the box on the total soil area (three and five-eights by nine and one-half inches) were recorded and the next cut made. Sixteen such areas were counted and the counts are shown in Table V. Three figures are given for each distance from the plant. The first number is the result of the count made on the freshly exposed soil area. The second number is the count of roots appearing on the glass front which was immediately in front of the section through the soil. The third row is the average of the count made on the glass front and the two adjacent similiar counts. The correlation coefficient is 0.8108, calculated from the average values for the glass front. This correlation is above the one percent level of significance for sixteen observations, and shows that the counts made on the glass front were a reasonably good estimate of the numbers of roots in the different areas of the box.

Tables IV and V show that the root distribution was fairly uniform throughout the box, yet the moisture disappeared from near the plant before an equal number of roots took moisture from a greater distance.

Measurements on individual roots were not as successful as measurements involving large numbers of roots in the boxes. An isolated root against the glass front was sampled along its length by removing the glass and taking soil samples and repeating the procedure after five days. Other roots were sampled at intervals of less than five days but the measurements are more erratic than the amount of

TABLE V

Correlation of Roots in a Cross Section of Soil and an Area Exposed to a Glass Wall. From Left to Right the Numbers Read from Near to Far from the Plant.

Area	Number of Roots: Inches From Plant															
	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48
Soil Section	54	50	47	41	49	58	67	56	62	48	66	60	64	62	59	40
Glass One Area	9	12	9	16	17	20	21	15	6	16	15	13	17	25	12	9
Glass Average of Three Areas	9	14	12	11	14	17	20	14	10	15	13	16	20	21	14	9

r = 0.8108

moisture taken in that time by the root. The first series of samples from a single root are shown in the upper row of Table VI. Five days later the samples were taken on the opposite side of the root and are shown in the lower row of Table VI. Some variation due to the soil and the sampling would be expected but not as much as is shown near the root. During the same five days a nearby sample, unaffected by the root, decreased from 20.21 to 19.12 percent moisture.

The area between two roots was sampled after the roots had been established for three days. The roots were one and one-eighth inches apart and the samples were taken at various intervals between the roots as shown in Table VII. The moisture in soil free of roots at the same time was 20.14, 20.71, and 20.93 for three samples. There is no apparent

TABLE VI

Moisture Reduction Caused by a Single Root

Date:	Percent Moisture					
April 6	15.48	19.05	19.60	20.31	19.85	21.54
April 21	12.19	15.15	11.71	13.90	15.58	17.58

TABLE VII

Moisture Percentages Between Two Roots

Inches from First Root					
000	0.125	0.250	1.00	1.125	1.250
First Root				Second Root	
21.78	19.78	20.54	20.06	20.99	21.07

effect due to absorption of water by roots.

Two corn plants were transplanted into long cylinders so that the roots were surrounded by soil at different moisture percentages as shown in Table VIII. The different layers of soil were separated with wax-paraffin seals to prevent moisture transfer. That these seals were not effective is indicated by the change in moisture percentages shown in Table VIII. The increase in moisture in the A layers may be attributed to a moist soil which was maintained above these layers, and was necessary to keep the roots alive. The transfer of moisture from C to D and D to E by plant 1 if attributed to roots is contrary to the transfer predicted by Breaseale since the movement shown is away from the plant. The movement of moisture from layer B through C to D under plant 2 is interesting because moisture apparently moved through a wax seal into a dry soil without appreciably changing the moisture in a layer of soil through which the water apparently passed. The two plants shown in Table XIII are the only

TABLE VIII

Change in Moisture Percentages in Soil Columns Under Two Corn Plants.

Layer of Soil	Plant 1		Plant 2	
	Original Percent	Final Percent	Original Percent	Final Percent
A	19.59	23.09	5.14	7.29
B	0.89	4.29	19.59	15.25
C	19.59	16.53	5.14	5.29
D	0.89	4.16	0.89	2.93
E	5.14	7.02		

two of five transplanted plants which survived for a week. One hundred grams of dry soil was used in each of the layers shown in Table XIII, so the moisture percentage changes are nearly the same as the grams of water transferred a distance of from 100 to 169 millimeters, through a wax seal over an area of 78.5 square centimeters. Any of this moisture movement would not likely be due to a plant which itself had only enough water to revive during the night, after wilting in the evening. The air temperatures at the time these plants were alive fluctuated in a daily cycle from a minimum of 60° F to a maximum of 80° F. Possible explainations were the roots, even though closely surrounded by the wax, acted as a wick, or that the moisture actually moved through the wax seal. It seems much more likely, however, that the seal was not perfect and moisture moved down the sides of the tube as vapor or liquid. Check tubes with the same moistures but without the corn plants were set up at the same time. In the check tubes the color of the air dry soil was seen to change, but no moisture samples were taken. The check tubes were observed near the minimum temperature and found to have beads of moisture on the sides of the glass even in the dry soils, and it was thought at that time that the check tubes were imperfectly sealed.

A corn plant was grown in a long tube so that roots several inches long could be washed from the soil without injury. Nine of these roots were placed in nine vials. Each vial contained 60 to 70 grams of soil. The soil was at three moisture levels, air dry, seven percent, and twenty percent. Nine vials without roots were prepared, all in the same way, and sealed with the paraffin-wax mixture. The losses of moisture are shown in Table IX. Although an inch of root was left between the vial and the plant, the roots affected the weighings, by exerting either a pull or a push on the vial, so that readings closer than one gram were erratic. All of the vials were suspended above the balance on a platform and the vials set off one at a time for weighing. The first weights were taken when the roots had been in the vials for three days the next weights at the end of a week. The plant was then cut away, the vials reweighed, the wax seals removed and the vial weighed again. The vials were then weighed at weekly intervals and found to lose moisture at about the same rate. The negative value in the moisture used by the plant for the period three to seven days for the moist soil probably is due in part to error in weighing and partly to the greater loss of moisture from the check vials. In no case did the plant exude moisture into the dry soil. All of the roots of the plant except those shown were in a jar of water. The losses from the free water were not recorded.

The two experiments with transplanted roots, and the many plants which were lost in making treatments used, indicate that future work will need to be confined to plants growing into the soil and subsequent moisture levels obtained by wetting different areas of soil. Also, the paraffin seals are not to be relied upon when small moisture movements are to be measured. Soil of the same moisture content without seals may be used as checks.

TABLE IX

Losses of Moisture in Grams from Vials Containing Roots and From Vials Not Containing Roots. A B and C are Replicates of the Same Treatment.

Period:	Air Dry Soil				7 % Moisture			20% Moisture		
Days	Vial	Root	Check	Loss	Root	Check	Loss	Root	Check	Loss
9-3	A	2	2		2	1		5	2	
	B	3	1		2	0		4	1	
	C	2	2	2	3	1	5	4	1	9
3-7	A	1	0		1	1		0	0	
	B	0	0		1	1		-1	1	
	C	1	2	0	0	1	-1	-1	3	-6
7-14	A	0	0		1	1		2	4	
	B	0	0		1	1		3	1	
	C	0	0	0	1	1	0	3	1	2
14-21	A	2	0		1	1		6	5	
	B	0	1		1	2		5	6	
	C	0	1	0	1	2	-2	4	5	-1

Four glazed two gallon pots were filled with weighed Gila silt loam soil and ten corn plants planted in each pot. An attempt was made to correlate growth of the tips with tensiometer readings at twelve hour intervals. The tensiometers did not hold up under the heat and drying conditions encountered and measuring the growing tips resulted in the injury and death of some of the plants. The tensiometers were removed the soil surface resealed with wax and the plants thinned to five healthy plants per pot. When all five plants were wilted so that they did not recover over night in a moist room where the relative humidity, determined with a sling psychrometer, was eighty percent and the temperature 31°C, the plants were considered wilted. The pots were in the moist room for six days continuously just before wilting and had been grown in the pots for two months. The results of these wilting points determinations are given in Table X, together with the results of wilting determined on the Clarion silt loam at Ames. The Gila silt loam retained 6.61 percent of moisture when the plants were permanently wilted. The range of the determinations of four pots was from 6.04 percent to 6.93 percent.

The pots at Ames were treated in different ways. In the first set of six pots corn was planted in moist soil and allowed to grow until wilting occurred. The first two pots were sampled when the central leaf was first wilted. The second pair was placed in the moist chamber and sampled when the central leaf remained wilted; they appear in Table X as jars three and four. Two other jars were allowed to remain in a wilted condition for seven days at which time the plants were nearly dead. One percent of moisture was lost in the first day after wilting and two an one-half percent in a week after wilting. The effect of salt on the wilting point is shown in the series in Table X marked Salt series. Without salt these samples checked fairly closely with the severly wilted plants of the first set. Additions of five-tenths and one percent Sodium Chloride resulted in wilting at moisture percentages near those of the first wilting point determinations.

TABLE X

Wilting Point Determinations on
Clarion Silt Loam and Gila Silt Loam.

Clarion Silt Loam	Pot	Moisture Percent of Samples				Average
Tip Wilted	1	10.46	11.09			
	2	11.18	11.20			10.98
Tip Badly Wilted	3	10.16	9.67			
	4	10.23	9.80			9.96
Wilted One Week	5	8.61	8.51			
	6	8.39	8.39			8.48
Salt Series						
Soil Only	1	8.38	8.36	8.37		
	2	8.39	8.11	8.25		
	3	9.72	9.02	9.37		8.66
0.5 % Salt	4	9.31	8.81	9.06		
	5	9.53	9.39	9.46		
	6	10.15	9.86	10.00		9.51
1 % Salt	7	10.42	10.14	10.28		
	8	10.31	10.88	10.60		
	9	11.25	11.35	11.30		10.72
					Pot Average	
Gila Silt Loam	1	6.79	7.15	6.84	6.93	
	2	6.49	6.51	6.71	6.47	
	3	7.23	6.85	6.59	6.89	
	4	6.39	5.70	6.04	6.04	6.61

The moisture percentages calculated for the Gila soil from another series of two gallon pots are shown in Table XI. After the top layer of paraffin and two inches of soil had been discarded, the samples were taken at three depths. Depth one was the layer just under the discarded layer of soil. Depth two was taken near the center of the pot and depth three from the bottom inch of soil, which was completely filled with roots. Sample "a" was always taken before sample "b", but the interval of time was a matter of seconds and these are considered as duplicate samples. Analysis of variance shows that the pots were different, or that in only five percent of samples drawn from a normal population would differences as great as those found between pots be expected. If the interaction of depth and pot were used as the error term the differences in pots would not reach the five percent level of significance. The average moisture content of 6.76 percent was used in later work as the wilting point of the soil. This analysis shows that there was no significant difference between the samples taken at different depths in the pots in the manner described. The analysis as shown serves to illustrate the fact that wilting point determinations when run simultaneously on the same lot of soil with plants as nearly alike as possible are more variable than the samples from a single pot. The determination of the wilting points is not precise and most wilting determinations should be considered as having a considerable range. One percent would not be a large difference in wilting point determinations.

Ten plants in each of four pots filled with Gila silt loam were measured for height each day from August first to September twenty-third, 1938 in another attempt to determine the growth of the plants in relation to

TABLE XI

Wilting Point Determinations on
Four Similiar Pots of Gila Silt Loam.

Pot		Moisture as a Percentage of Oven Dry Soil			
		Depth 1	Depth 2	Depth 3	Pot Average
I	a	6.300	7.042	6.851	
	b	6.739	6.293	6.380	6.601
II	a	6.882	7.459	6.899	
	b	7.253	8.125	7.392	7.335
III	a	5.844	6.396	6.273	
	b	7.266	6.699	5.787	6.376
IV	a	5.141	7.105	7.904	
	b	6.100	7.041	7.153	6.741
					6.7635

TABLE XIA

Analysis of Variance

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square
Total	23	10.823684	0.470595
Depth	2	1.395569	0.697785
Pot	3	3.015540	1.005180*
Depth x Pot	6	3.583737	0.597290
Samples within Pot within Depth (error)	12	2.818838	0.234903

* Probability less than five percent.

their water absorption. The pots were not sealed with paraffin until August 15. The height measurements were made on the tallest leaf. The measurements made on the leaf were more variable than those made on the growing tip. A single leaf attained its greatest height and stopped growing before the next leaf had attained a length as great as the first leaf. The curves for a single plant increase would result in a stair-stepped curve. The totals of ten plants gave a more or less continuous curve. The moisture percentages of the soil in the pots werecalculated from the oven dry weight of soil in a pot, determined from the final moisture percentages of the soil, and the weights of pot and wax added. The data are shown in Table XII. The growthsin Table XII are the total increase for the ten plants in the pot in millimeters during the number of hours at the left of the table. The percentages of moisture corresponding to the growth were calculated from the gross weight of the pot at the time the measurements of growth were made. The first column is the date in 1938 and the second column is the time in hours elapsed since the previous measurement.

The plants in all cases ceased to grow before the wilting point was reached. This fact is particularly well illustrated in the period August 16 to September 10 when the pots were watered when the weights showed they were within three percent of wilting. None of the plants wilted in this

TABLE XII

Increases in Height in Millimeters of Ten Corn Plants in Each of Four Pots in the Greenhouse at Tucson, Moisture Percentages in the Pots at the Time Measurements were made.

Date	Hours	Pot I Moisture	Pot I Growth	Pot II Moisture	Pot II Growth	Pot III Moisture	Pot III Growth	Pot IV Moisture	Pot IV Growth
8-2	28.8	16.96	253	19.42	394	26.89	327	11.80	250
8-3	17.8	14.61	270	16.73	146	23.65	352	15.09	197
8-4	29.8	10.48	110	11.52	137	15.86	311	10.86	80
8-5	19.5	9.63	-6	10.37	35	13.21	169	9.74	57
8-5	6.8	8.79	-58	9.34	0	10.92	12	9.01	-13
8-6	14.5	8.56	-29	9.09	-16	10.57	19	8.80	-48
8-7	25.0	7.82	0	7.99	-13	8.90	-22	7.93	- 3
8-8	25.5	7.10	-13	25.63	0	7.75	-19	7.16	-16
8-8	7.0	21.24	54	23.40	51	32.54	38	24.32	0
8-9	14.0	20.63	95	22.65	66	31.55	92	23.60	115
8-10	26.0	15.86	139	17.55	273	25.06	169	18.01	152
8-11	24.0	11.97	82	12.99	166	18.66	225	13.25	187
8-12	23.8	9.59	-16	10.02	-4	12.42	38	10.33	-22
8-15	60.0	7.02	-6	6.91	10	7.54	-25	7.48	-19
8-15	5.0	22.29	-121	25.51	-185	35.47	-359	25.49	-444
8-16	17.0	21.84	51	22.62	-72	31.62	-35	22.16	-13
8-17	26.5	16.58	104	17.24	90	23.67	96	16.58	64
8-19	43.0	11.41	84	10.93	165	13.24	133	11.07	82
8-22	79.2	10.67	201	10.08	270	10.81	97	10.73	160
8-23	15.8	22.48	59	24.45	44	34.05	82	23.84	44
8-24	23.5	16.83	34	18.62	179	26.76	116	17.83	57
8-26	24.0	10.76	60	10.70	61	15.02	191	11.19	52
8-27	26.0	16.74	51	18.48	83	24.64	12	18.33	109
8-28	21.7	12.81	8	13.31	58	17.61	94	13.70	49
8-29	23.9	10.70	4	10.84	2	13.17	6	11.20	3
8-31	57.3	8.44	-37	8.30	-30	9.50	21	8.68	-47
9-9	208.8	13.67	354	14.71	324	16.10	-149	18.24	139
9-10	25.4	16.81	106	18.98	97	25.24	91	18.41	168
9-11	23.0	12.98	42	13.39	64	19.13	53	14.00	92
9-12	27.8	10.25	12	10.24	15	12.13	4	10.67	2
9-13	23.2	9.32	-17	9.48	-25	10.47	-4	9.48	-6
9-14	23.8	8.74	-46	8.79	- 8	9.82	-91	8.98	-48
9-15	22.3	8.42	-1	8.27	-20	9.31	0	8.56	-5
9-16	20.5	7.96	-16	8.03	-7	9.08	-97	8.40	-22
9-17	22.9	7.73	-14	7.73	-9	8.57	-69	8.11	-25
9-23	106	6.77	-	6.76	-	6.76	-	6.75	-

period. On August 31 the maximum temperature for the day was 28°C at 5:00 P. M. The soil in all pots was above the wilting point yet the plants in all pots except number three were decreasing in height.

The history of wetting and drying of the soil in each pot can be read vertically on Table XII. Because of an error in calculating the soil contained in Pot III, too much water was added to this pot when it was wet. The measurements were to have been taken each twenty-four hours but other work interfered so that the readings were irregular in time. There were also periods when the measurements could not be taken at all and these contribute irregularities to the growth measurements. Table XIII shows a summary of the moisture percentages at the end of the growth periods for the four pots. The moisture percentages shown are the average for the period during which growth ceased or decreased. One instance where growth stopped and then continued again occurred. Pot II decreased in total height of plants from August 11 to August 12 and increased ten millimeters from August 12 to August 15. The moisture shown for this cessation of growth in Table XIII is the average of the moisture for the three dates. Pot III measurements showed an increase from August 29 to August 31 followed by a decrease. Since the time interval from August 31 to September 9 is long and included another wetting the point of growth cessation at this time was taken as the single figure 9.50 percent moisture on August 31. The decrease in growth in Pot III in the period August 31 to September 9 was not due to lack of moisture but to excess moisture.

TABLE XIII

Moisture Percentage in Pots at the Time Growth Stopped. Moistures are Average Percent Moisture per Pot.

Pot I	Pot II	Pot III	Pot IV
10.055	9.855	9.735	9.375
10.760	10.02	9.980	11.740
9.570	9.570	9.50	9.940
9.785	9.860	11.300	10.075

Average	9.88
Wilting Point	6.76
Average Available	3.12

The moisture percentages calculated from different moisture changes for different periods of measurement and for successive measurements are remarkably uniform. Corn plants in the same pots could remain alive and resume growth after the soil had been depleted to seven percent moisture and corn finally extracted the moisture to an average of 6.76 percent on September 23. No increase in height occurred below the point of growth cessation and the plants did not appear wilted at the time the plants stopped growing in the period from August 29 to August 31. During this period the moisture percentages were as shown in the third row of Table XIII. The average of the sixteen percentages in Table XIII is 9.884. The wilting coefficient calculated from the moisture equivalent was 9.10, but the determined wilting percentages from Table XI was 6.76 percent.

The hourly increases in leaf height per pot were calculated from the data in Table XII and are tabulated in Table XIV, with the percentage of moisture in the soil at the time the measurements were made. The data in Table XIV are arranged in order of pot and date reading from August 2 on Pot I to September 12 on Pot IV. A break in the numbers denotes a change from one pot to the next.

Many of the data from Pot III were omitted in Table XIV because the moisture percentage was higher than the range in which the plants would grow. Data from conditions of excessive moisture would not satisfactorily represent growth on a drying curve. The data in Table XIV represent the change in growth rate as the moisture percentage of the soil decreased. The correlation coefficient 0.4741 for the seventy-six determinationsof growth is above the one percent level of significance. Inspection of the data in Tables XII and XIV shows that less growth occurred just after the soil was wet than would occur in the next few days.

TABLE XIV

Moisture Percentages and Total Increases in Plant Height in Millimeters per Pot per Hour.

Percent Moisture	Rate of Growth	Percent Moisture	Rate of Growth
Pot I		Pot III	
16.96	0.8785	15.86	1.0436
14.61	1.5169	13.21	0.8667
10.48	0.3691	10.92	1.7779
21.24	7.7144	10.57	1.3104
20.63	6.7858	18.66	9.3751
15.86	5.3462	12.42	1.5967
11.97	3.4167	23.67	3.6227
21.84	3.0000	13.24	3.0930
16.58	3.9245	10.81	1.2247
11.41	1.9535	17.61	4.3318
10.67	2.5378	13.17	0.2609
22.48	3.7342	9.50	0.3660
16.83	1.4468	19.13	2.3043
10.76	2.5000	12.13	0.1439
16.74	1.9616		
12.81	0.3687		
10.70	0.1739		
13.67	1.6938		
16.81	4.0672		
12.98	1.8261		
10.25	0.4317		
Pot II		Pot IV	
19.42	1.3680	17.80	0.8681
16.73	0.8202	15.09	1.1067
11.52	0.4597	10.86	0.2685
10.37	0.1795	9.74	0.2923
23.40	7.2859	23.50	8.2143
22.65	4.7143	18.01	5.8462
17.55	10.5001	13.25	7.7917
12.99	6.9167	16.58	2.4151
17.24	3.3962	11.07	1.9070
10.93	3.8372	10.73	2.0202
10.08	3.4090	23.84	2.7848
24.45	2.7848	17.83	2.4255
18.62	7.6170	11.19	2.1667
10.70	2.5417	18.33	4.1924
18.48	3.1923	13.70	2.2581
13.34	2.6728	11.20	0.1304
10.84	0.0870	18.24	0.6651
14.71	1.5502	18.41	6.4462
18.98	3.7219	14.00	4.0000
10.24	0.5396 r = 0.4741	10.67	0.0719

the correlation coefficient and might reasonably be discarded. The slow start was caused by the fact that the leaves had been checked in growth by the low moisture but several days sometimes elapsed before the young leaves, themselves growing rapidly, reached the height of the old leaves. No negative growths are included in the correlation because the negative growths were caused by necrosis of the leaf tips which occurred particularly on those leaves which were young and tender at the time the plants suffered for water. The rate of dieing back depended on the age of the leaves in the pot and might be greatly increased by one tender leaf.

A significant correlation coefficient over the irregular hours of measurement, including the period just after wetting, and excluding the negative growth at low moistures, indicates that a much higher correlation could be obtained in a more carefully controlled experiment. Correlation of growth and percentage available moisture also might increase the correlation coefficient.

2. Corn Grain Osmometer

Corn grain was used as an osmometer to measure the relation of soil moisture to the tension with which water is held in the soil. It was first thought the absorption by the grain of the water from the soil might not reach a state of equilibrium. The first experiments were run at Ames to determine whether or not equilibrium between the water of the corn and the soil would be reached. Quart jars half full of corn and soil were kept at a constant temperature and mixed daily. At the end of three weeks the final moisture percentages of corn and soil were determined. A loss of total moisture which could not be accounted for occurred in these experiments. The procedure was changed to small, 60-70cc jars which had cork seals and aluminum screw caps. The loss in gross weight of these jars in three weeks ranged from a gain of one-tenth gram to a loss of three-tenths of a gram. The jars were weighed only to the nearest tenth and the gains may have been errors in weighing. In the first experiment the soil from the pots in which the wilting point had been determined was used in an attempt to find if grain and soil would come to equilibrium near the wilting percentage.

The soils used were the thoroughly mixed soils from each of four pots of Gila silt loam, the moisture percentages of which are shown in Table X. The soil from Pot I after sampling for the moisture at wilting was mixed by rolling on a large sheet of paper and then used to fill the jars. The jars were weighed, the corn was filled to one-third, one-half or two-thirds the volume of the jar and the total jar and corn weight read. The corn used was taken from a uniform lot of air dry grain. The soil was then filled to the top of the jar. Mixing settled the soil through the corn so that after stirring the mixture filled the jar only to the shoulder. The jars were all mixed by revolving in two planes. Part of the jars were not stirred again, some were stirred each week and some were mixed in the same way each day. The three ratios were each subjected to the three stirring intensities on each of the four soils. Two replications were used. The analysis of variance of the final moisture percentages of corn and soil is shown in Table XV. The very low moisture variability in the soil was due to the extremely low moisture in the soil. The range of moisture in the soil was from 1.01 to 1.04. The ratios do show a significant difference. The analysis of the corn moisture shows a similiar result except that the corn absorbed more moisture from some soils than others. The increase in moisture for the corn in the different soils shows that although the soil was dried uniformly the corn had not been able to get as much moisture from some soils as it could get from other soils. The uneven moisture in the corn indicates that the corn had not reached equilibrium with the soil and that the soil was dried so low that the absorption power of the corn was not great enough to obtain appreciable quantities of moisture from the soil. Stirring did not increase the amount of moisture absorbed nor effect the results in any way. Stirring was abandoned in later experiments after the seed and soil were once thoroughly mixed.

TABLE XV

Analysis of Variance of Moisture Percentages at the End of the Mixing Experiment December 1, 1937.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square
Soil			
Total	71	.0078	
Soil (S)	3	.0002	.000067
Ratio (R)	2	.0029	.00145**
Intensity (I)	2	.0004	.0002
S X I	6	.0002	.000033
S X R	6	.0013	.000216
R X I	4	.0003	.000075
Remainder	48	.0025	.0000521
Corn			
Total	71	639.77	
Soil (S)	3	32.03	10.68**
Ratio (R)	2	459.21	229.61**
Intensity	2	2.64	1.32
S X I	6	11.82	1.97
S X R	6	14.70	2.45
R X I	4	10.11	2.53
Remainder	48	109.26	2.30

** The figures which bear the double asterisk denote a significant difference as great as or greater than the one percent level.

The soil for the next experiment was obtained by mixing all of the soil not used in the preceding experiment and wetting to approximately ten percent moisture. The soil was allowed to stand for several days and mixed again before it was used. The moisture percentage after the second mixing was 9.62. The same three ratios of grain to soil used in the preceding experiment was used. The corn was air dry, or six percent moisture, when placed in the vials. The jars were set in a room at constant temperature, 31° within a range of one degree. Some of the jars were taken out at the end of two days, some after four, and eight days, some after two weeks, another series at the end of three weeks and the final series at four weeks. Four replications were made of each of the three ratios and six times before final determinations.

A significant difference in the residual moistures in the corn and soil was shown between the different ratios used. If the remainder is used as an error term for the variances due to the different times, and the interaction of times and ratios for the soil moistures, both the interaction and the times show a significant difference. After six days no appreciable changes occurred in the total percentage of the soil. The changes that did occur after six days were erratic and small. In subsequent experiments the time was set at seven days because this was a convenient schedule and equilibrium was reached before seven days. Corn of twenty

TABLE XVI

Analysis of Variance of Moisture Percentages at the End of the Mixing Experiment January 23, 1938.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square
Soil			
Total	71	118.30018	
Block	3	3.57708	1.19236
Ratio (R)	2	50.10297	25.0515**
Time (T)	5	12.05624	2.41124
R X T	10	25.52513	2.5525
Remainder	51	26.60587	0.52168
Corn			
Total	71	1260.8915	
Block	3	3.38926	
Ratio	2	1047.7665	523.88325**
Time	5	19.9847	3.99695
R X T	10	29.5764	2.95764
Remainder	51	159.6713	3.13080

** Figures marked with a double asterisk denote significant difference as great as or greater than the one percent level.

percent moisture with one ratio was in equilibrium with soil of essentially the same percentage as corn of twenty percent final moisture from another ratio. Since the most consistent figures were obtained with the smaller ratio, which was about eleven grams of corn in the air dry condition or (approximately ten grams of oven dry corn) and fifty grams of oven dry soil,

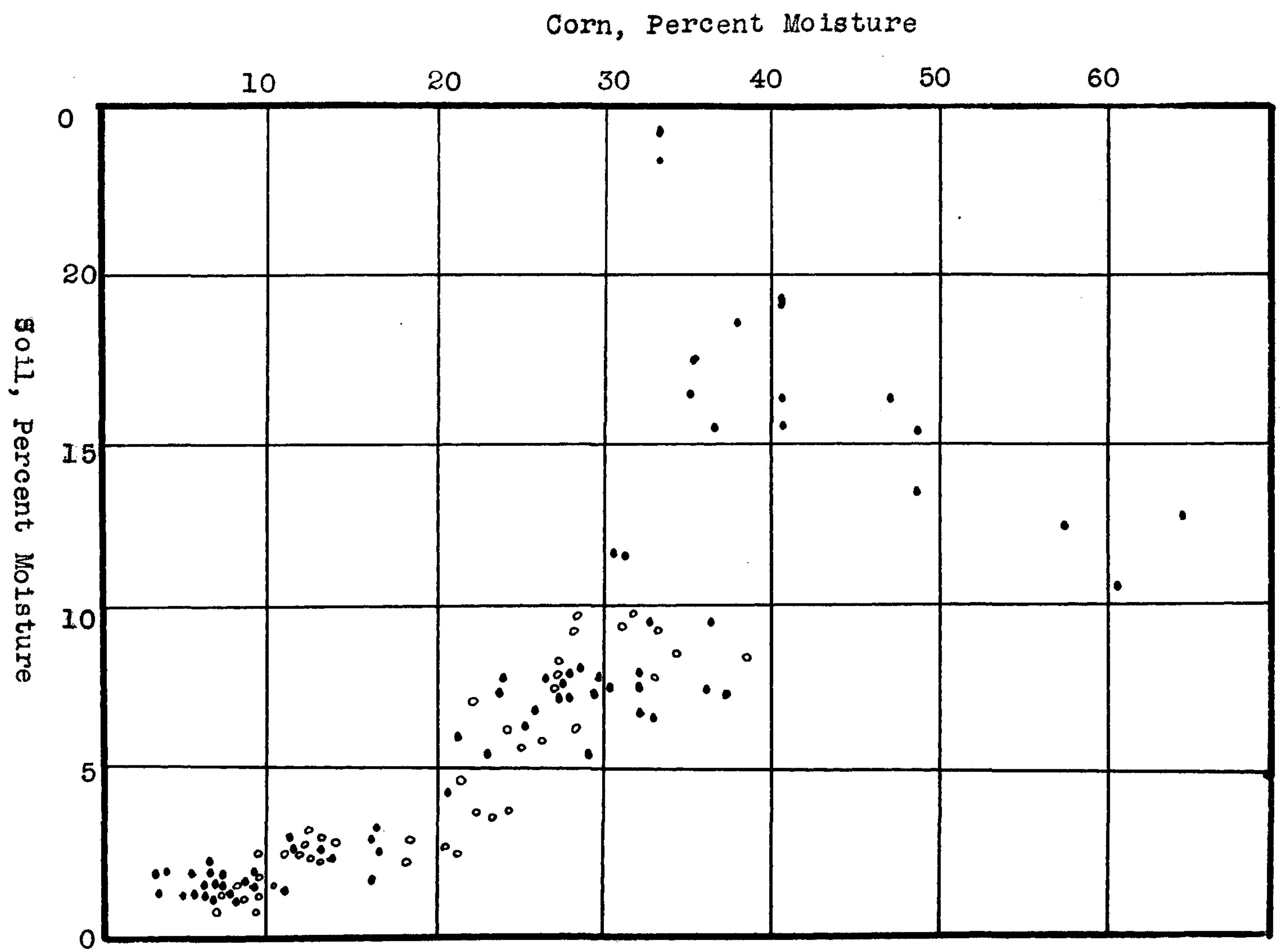

FIGURE V

Dot diagram of percentages of moisture distribution in soil and corn at equilibrium.

this ratio was used in later experiments.

A uniform lot of soil was divided into twenty equal portions. These different portions were wet to different moisture levels, ranging from air dry to thirty-six percent moisture. The soils and air dry corn used were placed in jars and after thorough mixing were allowed a week in which to attain equilibrium. The procedure was to thoroughly mix eleven grams of air dry corn with fifty grams of oven dry soil to which water had been added. The final moisture percentages of corn and soil are plotted in Figure V. Because of the similiarity of moisture in some of the samples there were no samples in which the final corn moisture percentages were in the range from eighteen to twenty percent. A second experiment was run in the same way with the original moisture content such that values fell within this range. The values determined in the second experiment are also plotted in Figure V and are shown as circles. Below two percent of soil moisture the corn grain was unable to absorb moisture from the soil. In a separate experiment the grain in a greater ratio to the soil was able to reduce the soil moisture to one percent. Both corn and soil were below air dry at the end of this experiment. The samples in which the soil held more than ten percent moisture and the corn held more than thirty percent moisture were erratic. The grain in many of the samples in this range germinated before reaching moisture equilibrium with the soil . Therefore, the effective upper limits of moisture for soil and grain equilibrium were ten percent soil moisture and thirty percent grain moisture. Below ten percent soil moisture corn seed would reach moisture equilibrium with the soil and since the wilting point was 6.76 percent, or in the range at which equilibrium was established, an attempt was made to standardize the absorptive power of the corn with sugar solutions, and thus to obtain an estimate of the force with which water was held in the soil. The osmotic values of the sugar solutions used were measured by the freezing point depression and are shown in column three of Table XVII.

Solution one was a saturated sugar solution from which sugar crystals were precipitated at the end of three days because the grain absorbed water from the solution. The percentage of moisture in the corn at the end of three days is shown in the fourth column of Table XVII. The moisture percentage of the corn was calculated from the oven dry weight of the corn as determined by the moisture of a parallel sample at the time of putting the corn in the solution. The calculated dry weights are shown in the fifth column of Table XVII. The moist corn after weighing was dried in the oven and these dry weights are shown in the sixth column of Table XVII. In solutions one and two, the final moisture percentages of the corn were in the range of moisture percentages obtained by grain in moisture equilibrium with the soil.

Grain in all of the weaker solutions was above the moisture percentage at which the corn would germinate in soil. The calculated dry weights of the corn and the actual dry weights of the corn check fairly closely except in solutions one and two in which the observed dry weights of grain were higher for some unknown reason than the calculated dry weights.

The indicated soil moisture tensions at the wilting percentages are in the neighborhood of 150 atmospheres. This value is not in agreement with published estimates (38) obtained with water vapor equilibria. Additional work will be required to determine the cause of the discrepancies and to establish the water competing power of the soil at the wilting percentage.

TABLE XVII

Osmotic Value of Solutions and Moisture Percentage of Corn After Reaching Equilibrium, with the Calculated Dry Weight at the Beginning and the Observed Dry Weight at the End of Three Days in the Solution.

Solution	Jar	Ov	Moisture Percent	Calculated Dry Weight	Observed Dry Weight
1	1	196.13	22.01	9.77	10.22
1	2	199.20	21.04	9.65	9.99
1	3	181.55	21.41	9.48	9.92
1	4	214.16	20.99	9.48	9.63
2	5	99.41	30.76	9.46	10.00
2	6	107.64	33.50	9.73	-
2	7	104.11	32.24	9.49	10.00
2	8	103.48	30.54	9.66	11.61
3	9	47.15	41.27	9.79	10.84
3	10	48.27	34.00	9.61	9.92
3	11	45.67	32.63	9.41	9.37
3	12	43.77	36.92	9.44	9.77
4	13	23.79	42.23	9.72	9.78
4	14	22.98	40.61	9.36	9.37
4	15	23.41	43.36	9.59	9.64
4	16	22.73	42.81	9.62	9.65
5	17	12.70	43.20	9.44	-
5	18	12.09	44.02	9.66	9.35
5	19	12.84	45.62	9.59	9.35
5	20	11.95	46.00	9.38	9.21
6	21	7.08	48.55	9.51	9.47
6	22	6.87	46.42	9.52	9.47
6	23	6.87	49.17	9.55	9.35
6	24	6.98	4[illegible].22	9.47	9.55
7	25	4.65	50.05	10.04	10.00
7	26	4.56	50.15	9.72	9.61
7	27	5.03	49.69	9.69	9.53
7	28	4.31	51.53	9.37	9.36
8	29	2.79	54.19	9.21	9.18
8	30	2.91	56.61	9.20	9.29
8	31	2.91	56.37	9.46	9.49
8	32	2.79	53.59	9.36	9.37
9	33	1.77	52.47	9.81	9.54
9	34	1.52	55.80	9.45	9.31
9	35	1.55	52.03	9.49	9.26
9	36	1.39	53.80	9.36	9.18
10	37	2.53	58.72	9.68	9.80
10	38	1.90	58.70	9.42	9.48
10	39	2.03	58.00	9.50	9.54
10	40	1.89	62.61	9.40	9.43

IV. DISCUSSION

Previous work on absorption of water by plants has been confined to moist soil, to water, or to nutrient solutions. It has been shown by the work of Miss Rosene that the absorbing zone of the root is not necessarily in the root tip or root hair region. In the studies presented here it was shown that corn roots absorbed water from soil at different rates depending on the distance from the plant. The differential absorption in relation to distance was found with moisture percentages within the range of tensiometer readings, during four drying periods. Two of the drying periods were after the roots had penetrated all of the soil area available. Below the range of easily available moisture the same directional gradient was observed. The roots near a corn plant absorbed moisture at and below the wilting point when the soil at a distance of three or four feet was near the field capacity of the soil. The corn roots were able to take moisture below the calculated wilting coefficient and even below the wilting point determined with plants from the same seed source. The absorption of moisture below the wilting point took place in soil near the plant while life of the plant was being maintained by moisture obtained at distances of more than two feet from the plant.

Data on growth show that in a soil, the wilting coefficient of which was 9.1 percent corn stopped growing when 9.88 percent of moisture remained in the soil. In the same soil the same plants removed the moisture to 7.00 percent and eventually to 6.76 percent when the plants were permanently wilted. Roots of corn plants in soils of different moisture content absorbed the moisture from soil having fifteen to twenty percent moisture but did not take water from or put water into soils with less than seven percent moisture. Such increased as did occur were shown by parallel checks to be due to permeability of the wax seals. The fact that the plants took moisture below the wilting point near the plant while the life of the plant was being supported by moisture farther away would indicate that a corn plant would not build up soil moisture percentages near the plant by drawing moisture from a greater distance.

The observations of the soil moisture loss from the soil, in the experiments performed, show that it is likely that a plant sets up an absorption gradient and that water close to the plant is more readily available even at low moisture percentages than moisture at a greater distance. Water, even though available, as measured by the wilting point, when at a distance of three to four feet was not absorbed rapidly enough by the plant to keep the plant from wilting. This observation introduces into the wilting point determination a factor of distance. The effect of distance on absorption of water by roots has not been studied previously and may explain some of the field observations where such crops as wheat and other grains have reduced the moisture at the end of the season to a point below the determined wilting point of the soil.

Root hairs can remain alive only in moist soils. Although they did have a persistence of two weeks in soil of more than fourteen percent moisture, root hairs could not withstand moisture levels of less than ten percent in soils where the wilting point was 8.6 percent. In one case a root tip was observed to have a film of moisture around the root hairs even though the root was in soil which was at eleven percent when the wilting point was 6.7 percent. Root hairs observed in the course of this experiment were temporary structures living in moist soils but were not active in water absorption when the plant was in relatively dry soil.

Evaluation of the forces in the soil moisture at the time the roots were absorbing the moisture was not found possible. The method of Shull with Xanthium seed was modified to use corn seed. The method as stadardized gave reproducable results in soil up to ten percent soil moisture and with the corn containing thirty percent grain moisture. Above the range mentioned results were erratic. Below one or two percent soil moisture corn grain was unable to extract moisture from the soil. Standardization of the corn in sugar solutions was uncertain because of unknown reasons. It is possible that Xanthium seed may be better material than corn for these determinations.

Data on the growth of corn on a drying curve show that the rate of increase of leaf length decreased as the moisture decreased to 9.8 percent of soil moisture when three percent of available moisture was still present. Below this moisture level the corn did not grow and in some cases even decreased in total length because of the drying of the leaves. Growth of plants in the field ordinarily takes place on a drying curve for the soil. Water added to a field soil, either as rain or by irrigation, wets thoroughly a layer of soil, the depth of which depends on the amount of water added and the previous wetness of the soil. The percentage of moisture to which a field is raised by irrigation or rain water may also depend on the previous moisture history of the soil. The wetting of the soil does not affect the nature of the water absorption by the plant except when the moisture is in such a small area or at such a distance, that the plant can not obtain the water. The soil is normally wet in a short time and is dried by plants absorbing water over a relatively longer time. The availability of the water in the soil depends upon moisture percentage and distance and since plants may be limited in growth before the soil reaches the wilting point, the relation between the plant, tops and roots, and the soil moisture is a dynamic state which will be changed by any changes in root growth, evaporation rate, transpiration rate, or soil moisture.

V. SUMMARY AND CONCLUSIONS

1. Corn was grown in a glass-front box so that the root distribution could be studied in relation to the regions of water absorption, as shown by tensiometers and soil moisture samples. Observation of roots on the glass-front gave a good estimate of the concentration of roots inside a box four inches wide and ten inches deep, as shown by a significant positive correlation between root counts made at the glass and root counts made on planes of soil perpendicular to the front.

2. The absorption zones of roots growing into the soil, when measured by tensiometer readings and soil moisture samples, appeared to be four inches or more behind the root hair region. Since roots continued to grow into a soil area after the first roots appeared in the area, the increase in number of roots may have affected the measurement of the difference in rate of absorption between the root hair zone and the area of root back of the root hair zone. No moisture absorption large enough to measure, with the methods used, was found in the root hair zones of the main roots.

3. Roots of corn plants absorbed moisture more readily near the corn plant than at a distance of three or four feet. Roots of growing corn plants extracted water below the wilting point in soil near the plant; when similiar

numbers of roots were present in soil well above the wilting point four feet from the plant. The water four feet from the plant was eventually absorbed after the soil near the plant was dried below the wilting point.

4. Growth measurements of corn plants were made when grown in pots in which the percentages of moisture were determined by weighing. The correlation between moisture and height increase was found to be positive and significant. Corn grew more rapidly when water was readily available than when the moisture approached the wilting point on a drying curve. Corn plants stopped leaf growth when the soil moisture percentage averaged 9.88 percent, for sixteen determinations. The wilting coefficient calculated from the moisture equivalent of the soil was 9.1 percent and the wilting point determined with the same plants in the same pots was 6.76 percent.

5. Corn grain was used as an osmometer in an attempt to determine the forces under which roots absorb water from the soil. The use of grain was shown to be impractical above ten percent soil moisture and thirty percent corn grain moisture. Grain used in soils so moist that the grain reached more than thirty percent moisture germinated, and did not reach equilibrium with the soil. Corn grain in sugar solutions had a higher moisture percentage than corn in equilibrium with soil except in the most concentrated solutions. Corn seed in concentrated sugar solutions for three days gained in dry weight, suggesting, sugar absorption by the grain.

The preliminary experiment indicates a force of about one hundred and fifty atmospheres in the soil water at the wilting percentage. This work will be checked in future experiments.

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VIII. VITA

Charles Homer Davis was born near Glendale, Arizona, February 13, 1912, to Homer Davis and Ollie Barkley Davis. He attended elementary school in Bisbee, Arizona, Los Lametas, California, and Glendale, Arizona. He graduated from the Glendale, Arizona high school and spent one year at the Phoenix, Arizona Junior College before entering the University of Arizona from which institution he received the degree Bachelor of Science in Agriculture in 1935. He was granted the Master of Science by Iowa State College in 1936.